ASSEMBLY RELIABILITY OF BGAs AND EFFECTS OF BOARD FINISH

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Abstract

A large number of test vehicles with two ceramic (361 and 625 I/Os) and five plastic (256, 313, 352-two types, 560 I/Os) packages and three surface finishes were assembled and subjected to two thermal cycling environments. The number of cycles to failure was determined.

This paper will present failure characteristics of the assemblies up to 7,000 cycles. The effect of three surface finishes (HASL, OSP, and Ni/Au) on cycles to failures and their failure mechanisms will also discussed in detail. The SEM microphotographs and elemental surface chemistry for random brittle failure of Ni/Au will be presented. Possible reasons for ductile and brittle failure behavior will also be discussed.

Introduction

Ball Grid Array (BGA) electronic packages are now in common use for commercial application and are being evaluated by the aerospace and military industry. These packages are replacing Quad Flat Pack (QFP) packages with higher pin counts. In addition to improved thermal and electrical performance, BGAs higher pitch (0.050 inch typical), better lead rigidity, and self-alignment characteristics during reflow processing also make them very attractive from the manufacturing aspects.

To understand and address many common quality and reliability issues of BGAs, JPL organized a consortium with sixteen members in early 1995. The diverse membership including military, commercial, academia, and infrastructure sectors which permitted a concurrent engineering approach to resolving many challenging technical issues.

Interim test results were presented in NEPCON West '98 conference. This paper will discuss the following:

- The update failure mechanisms of assemblies to about 7,000 cycles
- Differences in ceramic and plastic package failure mechanisms
- The effect of three types of surface finishes on failures and failure mechanisms

The finish effect will be emphasized. The board surface finishes studied included: (1) Hot Air Solder Leveling (HASL), the predominant surface finish in industry; (2) Organic Solder Preservative (OSP), a new and cost-effective coating, and (3) Ni/Au, an application specific finish.

BGA Test Vehicle Configuration

The two test vehicle assembly types were plastic (PBGAs) and ceramic (CBGAs) packages. Both FR-4 and polyimide PWBs (Printed Wiring Board) with six layers, 0.062 inch thick, were used.

Plastic packages covered the range from OMPAC (Overmolded Pad Array Carrier) to SuperBGAs (SBGAs). These were:

- Two peripheral SBGAs, 352 and 560 I/O
- Peripheral OMPAC 352 I/O, PBGA 352 and 256 I/O
- Depopulated full array PBGA 313 I/Os
- 256 QFP (Quad Flat Pack), 0.4 mm Pitch

In SBGA, the IC die is directly attached to an oversize copper plate providing better heat dissipation efficiency than standard PBGAs. The solder balls for plastic packages were eutectic (63Sn/37Pb).

Ceramic packages with 625 I/Os and 361 I/Os were also included in our evaluation. Ceramic packages had high melting solder balls (90Pb/10Sn) with 0.035 inch diameters. These balls were attached to the ceramic substrate with eutectic solder (63Sn/37Pb). At reflow, package side eutectic solder and the PWB side eutectic paste was reflowed to provide the electro-mechanical interconnects.

Plastic packages had dummy and daisy chains with the daisy chains on the PWB designed to be able to monitor critical solder joint regions. Most packages had four daisy chain patterns, 560 I/O had five, and the QFP had one.

Thermal Cycling

Two significantly different thermal cycle profiles were used at two facilities, conditions A and B. The cycle A conditions ranged from -30 to 100°C and had increase/decrease heating rates of 2°C and dwells of about 20 minutes at the high temperature to assure near complete creeping. The duration of each cycle was 82 minutes. The cycle B conditions ranged from -55 to 125°C. Cycle B could also be considered to be thermal shock, since it used a three regions chamber: hot, ambient, and cold. Heating and cooling rates were nonlinear and varied between 10 to 15 °C/min. with dwells at extreme temperatures of about 20 minutes. The total cycle lasted approximately 68 minutes. BGA test vehicles were monitored continuously to detect electrical failure and their failure mechanisms were characterized. BGA test vehicles were continuously monitored through a LabView system at both facilities.

Failure Mechanisms for Plastic Assemblies

Figure 1 includes a collection of SBGA and PBGA solder joints with voids at different locations in the solder joints. Generally, most of voids are close to the package side for PBGA assemblies. The upper right hand photo shows how cracks propagate in and out of a void. A crack initiated at the package corner interface and propagated into a void at a 45 ° angle and leave void parallel to the package interface. The two types of cracks represent a mix mode of stress conditions.

Note also that the large void in the lower left photo shows evidence of mounting materials from metallographic preparation. This is puzzling since there is no evidence of a through-crack. Perhaps a crack, normal to the photograph's cross section, has interconnected the void to the outer balls' surface. This reveals the complexity of failure modes and remind us of the caution that must be exercised when interpreting failures by two dimensional cross-sectioning. Ideally, a three dimensional characterization is needed to better interpret the results.

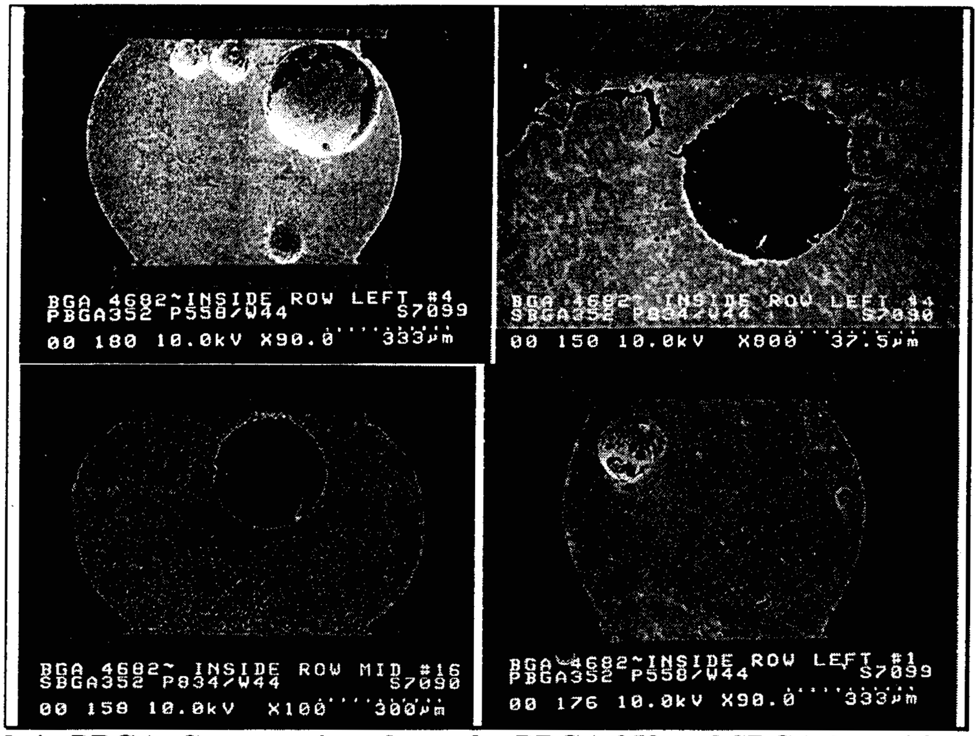


Figure 1 Voids in PBGA. Cross-section photos for PBGA 352 and SBGA 352 of Solder Balls with Void and Cracking after 4,682 cycles (-30°C to 100°C)

Package attachments were very weak after 4,500 B cycles and were easily detached from the board. Cycled packages were detached and balls were inked and their images were mapped. The ball map distributions for several detached SBGA560 are shown in Figure 2. All joint failures were not from the board interface. There appeared to some trend in their distribution.

Most balls were separated from the board interface for SBGA 560 on FR-4 boards as evidenced from the large number of dark spots which represent the balls on the package. This is not true for those on polyimide boards. There were more joint separations at the package side for polyimide boards, which might be due to the higher thermal stability of polyimide compared to FR-4 in the B thermal cycle.

Note also there was separation of one whole edge row from the package side. This might represents the existence of high warpage for the outer-package edge generally observed for the plastic packages. Similarly, mappings for other plastic packages were carried out and trends were studied.

For ceramic packages, mapping was not possible since most of the packages were already separated from the board at 4,500 cycles. Separations were mostly at the package interfaces since detached packages generally had no balls on them. In addition, several test vehicle boards had a large number of balls at the location of the ceramic package attachments.

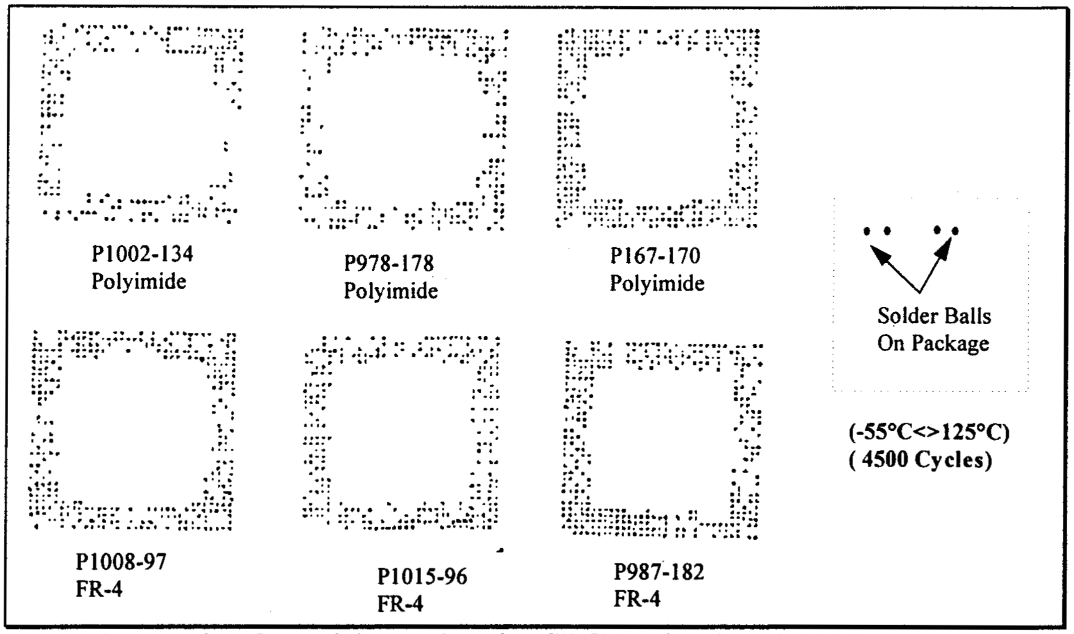


Figure 2 Map of board/package failure sites for SBGA 560 after 4,500 B cycles. Packages were detached and solder balls on the package were then mapped

Surface Finishes

The surface finishes considered for evaluation were 180 TVs with Organic Solderability Preservative (OSP), 14 electroless nickel/immersion gold, and 5 HASLs. The critical process factors for BGA assembly as well as reliability issues were considered during the selection of surface finish. Factors such as surface coplanarity, solder volume, solderability, moisture sensitivity, thermal aging behavior (shelf life) and second reflow were also considered when the PWB surface finishes were selected.

HASL

The predominant surface finish in the PWB industry has been HASL. In HASL, the tin/lead plating is accomplished by dipping the fluxed PWB into or by passing it over molten solder. The excess solder is removed by high velocity hot air which levels the remaining solder on exposed surfaces. The solder coatings are dense and have good adhesion, but are non-uniform and are not suitable for some emerging technologies.

This process is being replaced for several reasons including environmental and safety issues (hazardous waste/lead exposure), technological limitations (fine pitch device assembly), and equipment maintenance expenses. Alternate processes have been developed that are environmentally friendly, and provide a surface planarity equivalent to the plated copper finish, and require very little equipment maintenance.

OSP

OSPs, also known as anti-tarnish, are gaining popularity as a low-cost, high volume alternative to HASL and provide excellent surface coplanarity, required for fine pitch SMT applications. They are water based organic compounds (typically azole- benzotriazole or benzimidazole) that selectively bond with copper to provide an organometallic copper layer. OSP process temperatures usually do not exceed 150 °C, markedly lower than HASL process temperatures. Key drawbacks of OSPs include susceptibility to stain (water, flux, fingerprint) and deterioration as a result of the temperature heat cycles typically found in mixed technology.

For example, compatibility of OSP finish with aramid PWB might be an issue. This is primarily due to the hydroscopic nature of aramid which requires prebaking at high temperature before reflow. This process degrades the OSP. Another issue that must be considered is compatibility of OSP with flux. Water soluble finishes are more likely to form solder balls if the temperature profile and solder mask design are not optimized. No clean flux with use of nitrogen atmosphere flow might be the choice for some applications.

The OSP materials recommended by the PWB fabrictor was chosen for the test vehicle surface finish. The fabricator had used the coating for various BGA applications with no reported problems. One advantage of this coating was its higher tolerance to the higher temperatures commonly experienced during the drying stage.

Vendor data sheets indicate that the coating is a water-based OSP used to protect and maintain the solderability of printed circuit board copper surfaces. The active ingredient is designed to react with copper and copper alloys forming a thin uniform coating on circuitry. It is also reported that the coating was compatible with R, RMA, OA, No-Residue, and No-Clean solder pastes and fluxes. It has excellent solder wetting even after multiple reflow operations. Thickness is typically 6-8 microinch (0.15 to 0.18 micron).

Ni/Au

Although electroless nickel/immersion gold is more complex than OSP, they satisfy the application-specific requirements for fine pitch and chip-on-board (COB) assemblies. This process is a two-layer, gold-over-nickel metallic surface finish plated onto the copper base by chemical vapor deposition. Nickel is deposited on the copper by an electroless process resulting in a deposit thickness of 100 to 200 microinches.

The gold is then deposited in an exchange reaction replacing nickel on the entire surface with a thin layer of pure gold. The gold thickness is typically in the range of 3 to 5 microinches. Even though the gold thickness is not significant compared to that typically used for solder paste volume, the potential of solder joint embrittlement due to formation of intermetallic compounds with tin may be of concern. Ni/Au coatings are not reworkable, and are relatively expensive in terms of waste treatment and processing. The thickness of the gold was 3-5 microinches. The Ni/Au surface finish was carried out by the same company that did the OSP coating.

Failure Mechanisms For Different Surface Finishes

Ceramic package failure under A cycling conditions for PWBs with different surface finishes are shown in Figure 3. Both HASL and OSP failures, initiated at the PWB side, showed ductile features evidenced from the zigzag propagation through the eutectic solder joint. This generally was not the case for Ni/Au. For Ni/Au, several joints of a package showed brittle failure, which was first noticed during a routine visual inspection of the assemblies.

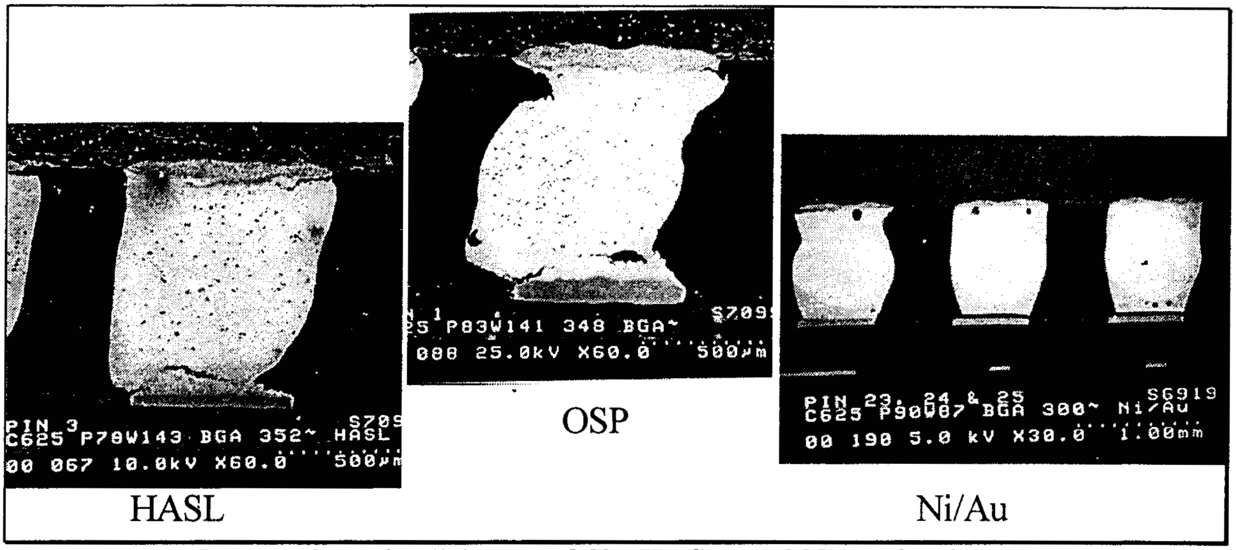


Figure 3 Failure Mechanisms for Joints on OSP, HASL, and Ni/Au Surface Finishes for CBGA 625 under A Conditions (-30°C to 100°C)

Brittle failure by the gold embrittlement could be one possible explanation, if the amount of gold exceeded three volume percentages of the solder joint. This was not the case, since the thickness of gold was controlled by an immersion technique to 3-5 μinch. To assure this was the case, a sample joint of Ni/Au surface finish was analyzed for various trace elements at PWB interfaces using the Energy Spectroscopy for Chemical Analysis (ESCA) feature of SEM.

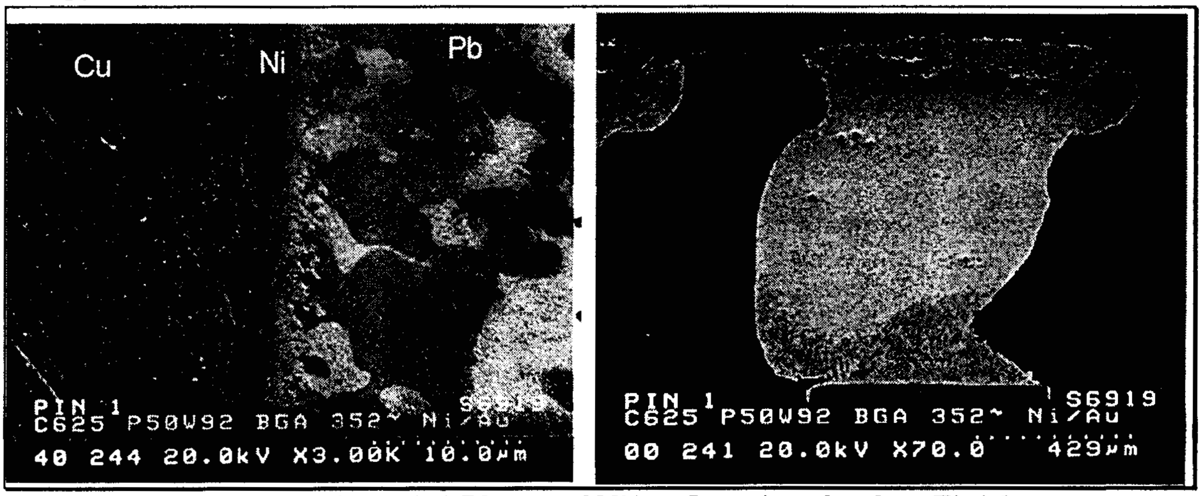


Figure 4 Magnified Photos of Ni/Au Interface Surface Finish

A cross-section photo with elements in each phase is shown in Figure 4. Qualitative elements detected by probing at various sections of the joint are also determined. No traces of gold were detected, possibly because the low amount of gold could have been dissolved during the reflow process. Other elements were as expected and included Cu, Ni, P, Pb, and Sn. Existence of phosphorus traces indicates the chemistry of the bath used for Ni plating. This element is found in a common chemistry used for the Ni surface finish.

Failure of Plastic Package with Ni/Au, OSP, and HASL

Figure 5, shows cross-sectional micrographs of the PBGA 256 after 6,800 A cycles. Photos are for three types of surface finishes, OSP, Ni/Au, and HASL. The failures are very similar to those seen previously for assemblies after 4,800 cycles with the OSP finish. There is no apparent difference of failure mechanisms among the three surface finishes. Ductile failure is the principal failure mechanism for the three surface finishes. Similarly to other plastic packages, failures were either at package or board side. Generally, voids were accumulated at the package interface.

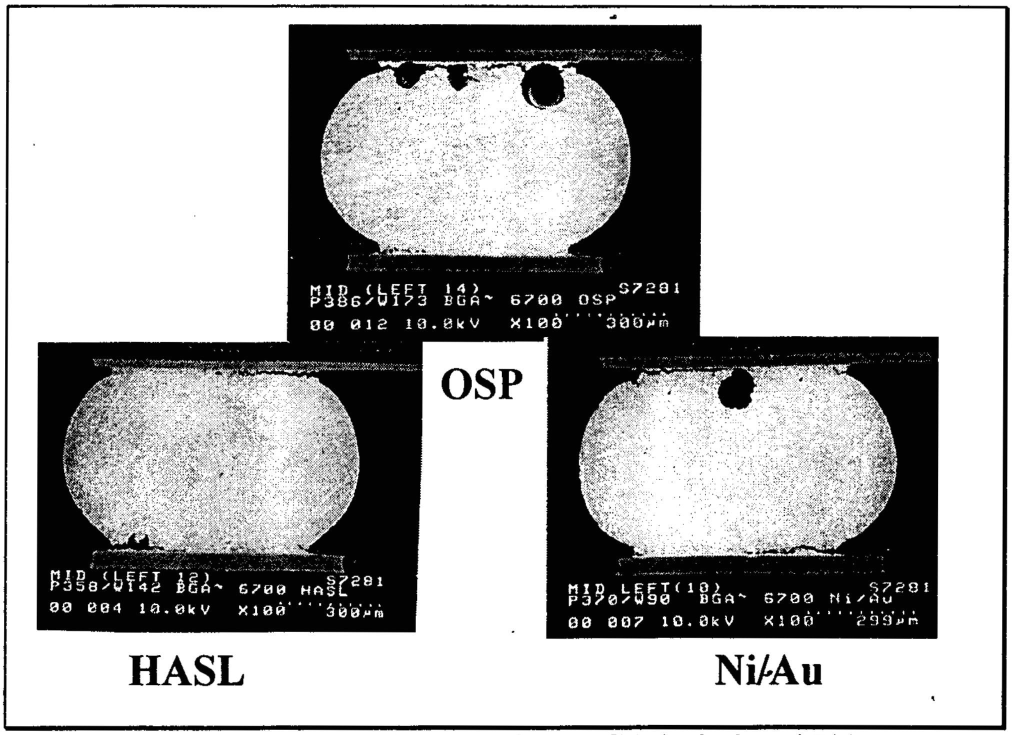


Figure 5 Surface finish and failure for PBGA 256 after 6,700 A cycles

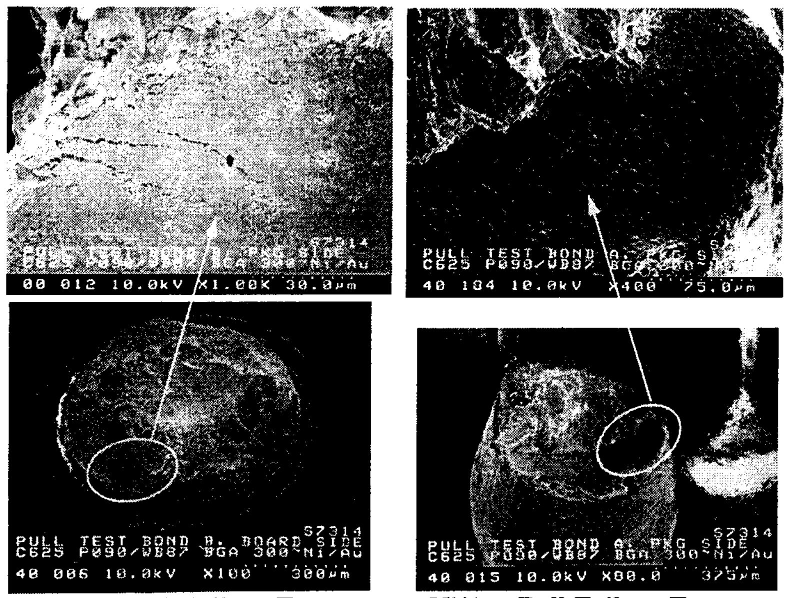
Further Evaluation of the Cause of Brittle Failure

Elemental characterization of brittle surfaces was obscured by the metallugraphic mounting materials. Results were not accurate. A virgin surface for the brittle behavior was needed for a more accurate surface analysis.

Remains of this package were pull tested under a sustaining load of 7 lb. The load was small and no separation was observed after two mounts at room temperature. No separation was observed after 5 days exposure at 100°C under the same load. The package was finally pried off. This techniques was not attempted at the beginning in order to avoid potential damage to solder joints.

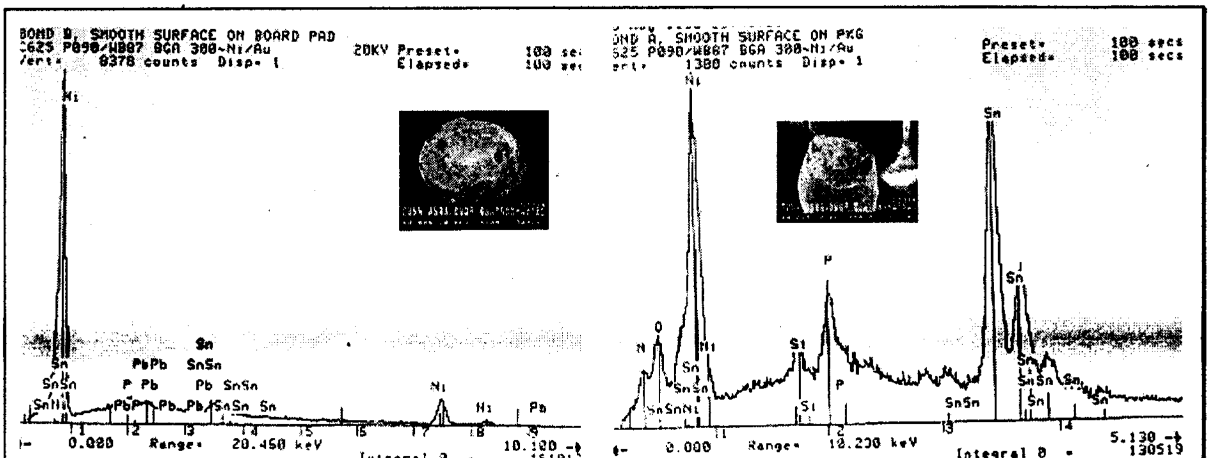
Out of 525 separated balls, only 13 balls remained on the board and the majority (525-13= 512) were still attached to the package. Out of 512 pad separations on the board, 470 were pulled from traces and 42 were by solder joint separation. Out of these 42, only 3 pads showed partial signs of brittle failure. The crescent surfaces were from 1/3 to about 1/4 of the pad area.

Figure 6 shows the SEM photographs for brittle failure features on ball and package pads. Figure 7 shows elemental analysis of the ball and pad surfaces by ESCA. For ductile failure regions, the elements were found to be Pb and Sn of eutectic solder composition, as expected. This was not the case for brittle surfaces. At the smooth ball surface, elements included Ni, P, and Sn, whereas at the pad surface, they were mostly Ni. Pimples on the ball surface were Sn.



Ni/Au, Board Failure Feature   Ni/Au, Ball Failure Feature

Figure 6 SEM photomicrograph of detached of ceramic package on Ni/Au surface finish with brittle areas



Ni/Au, Board Surface Chemistry   **Ni/Au, Ball Surface Chemistry**

Figure 7 Elemental chemistry of brittle surface shown in Figure 6

Conclusions

- For plastic packages, crack initiation, propagation, and failure occurred at either the package or board interfaces for sections with or without voids. This was true for A or B cycle conditions. Generally, voids were concentrated near the package interfaces. There appeared to be no crack propagation among the voids, except for the voids interconnected at the interface.
- For a ceramic assembly failure, brittle failure was observed for Ni/Au surface finishes. OSP and HASL showed ductile failure through eutectic solder joints. For plastic packages, there was no distinction between the three surfaces.
- Pull tests of assembly with Ni/Au brittle failure revealed only three localize brittle failures out 525 separated sites. This means that the potential of finding such random failure by a few cross-section examinations is very low. Brittle failure has been shown by bend tests by others.
- Elemental analysis of one brittle Ni/Au surface finish revealed no detectable gold, but a reasonable amount of phosphorous and Ni on the detached solder ball surface. Phosphorous segregation at the interface, surface contamination during Ni/Au plating or after plating by diffusion, and brittle fracture of Ni-P and Ni_3Sn_4 were shown to be the three potential failure mechanisms[1]. This is the case when the Ni/Au content is less than 1% and there is no potential of gold embrittlement.

REFERENCES

1. Mei, Z., et al "Brittle Interfacial Fracture of PBGA Packages Soldered on Electroless Nickel/Immersion Gold," 48th Electronic Components & Technology Conference (ECTC), May 25-28, 1998

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